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Aurore Franco, Cécile Lasserre, H. Lyon-Caen, Vladimir Kostoglodov, E. Molina, et al.. Fault kinematics in northern Central America and coupling along the subduction interface of the Cocos Plate, from GPS data in Chiapas (Mexico), Guatemala and El Salvador. *Geophysical Journal International*, 2012, 189 (3), pp.1223-1236. 10.1111/j.1365-246X.2012.05390.x . hal-00764116

HAL Id: hal-00764116

<https://hal.science/hal-00764116>

Submitted on 12 Dec 2012

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Fault kinematics in northern Central America and coupling along the subduction interface of the Cocos plate, from GPS data in Chiapas (Mexico), Guatemala and El Salvador

A. Franco^{1,3}, C. Lasserre², H. Lyon-Caen¹, V. Kostoglodov⁴, E. Molina^{5,6},
M. Guzman-Speziale⁷, D. Monterosso⁸, V. Robles⁹, C. Figueroa¹⁰, W. Amaya¹⁰, E. Barrier¹¹, L. Chiquin¹², S. Moran¹², O. Flores¹³,
J. Romero¹⁴, J.A. Santiago⁴, M. Manea⁴, V.C. Manea⁴

¹Laboratoire de Géologie, Ecole Normale Supérieure, CNRS, Paris, France

²ISTerre, Université de Grenoble 1, CNRS, F-38041 Grenoble, France

³now at Laboratoire de Géodynamique des rifts et des Marges passives, Université du Maine, UMR6115, Le Mans, France

⁴Instituto de Geofísica, Universidad Nacional Autónoma de México, Mexico

⁵Instituto Nacional de Sismología, Vulcanología, Meteorología e Hidrología, Guatemala Ciudad, Guatemala

⁶now at Universidad Mariano Gálvez, Guatemala Ciudad, Guatemala

⁷Centro de Geociencias, UNAM, Campus Juriquilla, Mexico

⁸Coordinadora Nacional para la Reducción de Desastres, Guatemala Ciudad, Guatemala

⁹Instituto Geográfico Nacional, Guatemala Ciudad, Guatemala

¹⁰Instituto Geográfico y Catastro Nacional, Centro Nacional de Registros, El Salvador

¹¹Institut des sciences de la Terre de Paris, CNRS, Université Pierre et Marie Curie, Paris, France

¹²Centro Universitario del Norte, Universidad de San Carlos de Guatemala, Coban, Guatemala

¹³Centro de Estudios Superiores de Energía y Minas, Universidad de San Carlos de Guatemala, Guatemala Ciudad, Guatemala

¹⁴Geología Ambiental e Economía, Guatemala Ciudad, Guatemala

26 January 2012

SUMMARY

New GPS measurements in Chiapas (Mexico), Guatemala, and El Salvador are used to constrain the fault kinematics in the North America (NA), Caribbean (CA) and Cocos (CO) plates triple junction area. The regional GPS velocity field is first analysed in terms of strain partitioning across the major volcano-tectonic structures, using elastic half-space modeling, then inverted through a block model. We show the dominant role of the Motagua fault with respect to the Polochic fault in the accommodation of the present-day deformation associated with the NA and CA relative motion. The NA/CA motion decreases from 18–22 mm/yr in eastern Guatemala to 14–20 mm/yr in central Guatemala (assuming a uniform locking depth of 14–28 km), down to a few mm/yr in western Guatemala. As a consequence, the western tip of the Caribbean plate deforms internally, with ≈ 9 mm/yr of east-west extension (≈ 5 mm/yr across the Guatemala City graben alone). Up to 15 mm/yr of dextral motion can be accommodated across the volcanic arc in El Salvador and southeastern Guatemala. The arc seems to mark the northern boundary of an independent forearc sliver (AR), pinned to the NA plate. The inversion of the velocity field shows that a 4 blocks (NA, CA, CO, AR) model, that combines relative block rotations with elastic deformation at the block boundaries, can account for most of the GPS observations and constrain the overall kinematics of the active structures. This regional modeling also evidences lateral variations of coupling at the Cocos subduction interface, with a fairly high coupling (≈ 0.6) offshore Chiapas and low coupling (≈ 0.25) offshore Guatemala and El Salvador.

Key words: Satellite Geodesy, Kinematics of crustal and mantle deformation, Seismic cycle, Subduction, Caribbean Plate, Central America.

1 INTRODUCTION

The complex surface deformation observed in northern central America results from the interaction between the North America (NA), Cocos (CO) and Caribbean (CA) plates (figure 1). The main active structures related to this interaction are the Polochic

and Motagua left lateral strike-slip faults at the NA/CA boundary, the north-striking grabens south and east of it in Guatemala and Honduras, the mid-America trench and the volcanic arc associated with the CO subduction under the CA plate (e.g., Plafker, 1976; Burkart, 1983; Burkart & Self 1985). In the past decade, sev-

Figure 1. Tectonic setting of the Caribbean plate. Gray rectangle shows study area of Figure 2. Faults are mostly from Feuillet et al., 2003. PMF: Polochic-Motagua faults. EF: Enriquillo Fault. TD: Trinidad Fault. GB: Guatemala Basin. Topography and bathymetry are from Shuttle Radar Topography Mission (Farr and Kobrick, 2000) and Smith & Sandwell (1997), respectively. Plate velocities relative to Caribbean plate are from Nuvel1 (DeMets et al., 1990) for Cocos plate, DeMets et al. (2000) for North America plate and Weber et al. (2001) for South America plate.

eral seismological and geodetic studies have tried to quantify the kinematics of these structures accommodating the active deformation (e.g. DeMets, 2001; Guzman-Speziale, 2001; Lyon-Caen et al., 2006) and to understand the different factors and the tectonic forces that control this deformation (e.g. Alvarez-Gomez et al., 2008; Rodriguez et al., 2009; Correa-Mora et al., 2009).

From GPS measurements and modeling, Lyon-Caen et al. (2006) documented a 20 mm/yr rate of the NA/CA relative motion in easternmost Guatemala, mostly accommodated across the Motagua fault. This rate decreases westwards, reaching nearly 0 mm/yr near the Mexico-Guatemala border, as part of the deformation is being transferred southwards into the grabens (mainly the Guatemala city graben). Lyon-Caen et al. (2006) also suggest a weak coupling at the CO/CA subduction interface and a dextral slip component across the volcanic arc in Guatemala. More recent studies (Correa-Mora et al., 2009; Rodriguez et al., 2009; Alvarado et al., 2011) have used a dense GPS network in Honduras, El Salvador and Nicaragua to build a regional model of the deformation of the western part of the Caribbean plate. A main outcome is that the extension relative to the stable Caribbean plate is not limited to Guatemala but is observed in a broader area (Guatemala and western Honduras, Rodriguez et al., 2009). Another important result is that coupling at the CO/CA subduction interface offshore El Salvador and Nicaragua, inferred from finite element modeling (Álvarez-Gómez et al., 2008; Correa-Mora et al., 2009), is likely weak as well. These models also suggest that the volcanic arc is a rheologically weak zone. It separates the undeformed, trench-parallel moving forearc, which is pinned to the NA plate (Correa-Mora et al., 2009; Alvarado et al., 2011), and the wedge-shaped western Caribbean plate, which inner deformation is influenced by the direction of the NA/CA motion relatively to the strike of the curved Polochic-Motagua fault system (Álvarez-Gómez et al., 2008; Rodriguez et al., 2009).

In this paper, we densify the Lyon-Caen et al. (2006) data set including a third campaign of GPS measurements in Guatemala. We also extend the study area using new GPS measurements in Chiapas (southern Mexico) and El Salvador. This allows us not only to refine previous results but also to complement the regional dataset

Figure 2. GPS network: campaign sites in Guatemala/El Salvador (black triangles), Chiapas and Mexico (open triangles) and permanent sites (white triangles with names in bold). MAT: Mid-America Trench, PF: Polochic Fault, MF: Motagua Fault, JF: Jocotan Fault, GG: Guatemala-city Graben, IG: Ipala Graben, HD: Honduras Depression, SF: Swan Fault.

and to propose a kinematic block model in the critical area of the triple junction between the CO/CA/NA plates. In particular, we discuss the present-day GPS derived coupling along the subduction zone from southern Mexico to El Salvador.

We first present the GPS dataset, the processing strategy and a first order analysis of the GPS velocity field in terms of strain partitioning across the major volcano-tectonic structures. The GPS velocity field at the regional scale is then inverted using the DEFNODE model that combines relative block rotations and elastic deformation due to coupling at the block boundaries (McCaffrey, 2002). Finally we discuss the implication of this new dataset and modeling for the understanding of the complex regional tectonics.

2 DATA AND PROCESSING

2.1 GPS sites and data acquisition

We use GPS data from 34 campaign sites (figure 2, Table 1): 23 sites in Guatemala, 3 sites in El Salvador, and 8 sites in Chiapas (southern Mexico). Data from 4 regional permanent stations belonging to the Servicio Sismología Nacional (SNN) mexican network (site TPCH) or to the International GPS Service (IGS) network (sites ELEN, HUEH, SSIA) complement this campaign data set (figure 2).

The first two campaigns of measurements in Guatemala were carried out in February 1999 and 2003 and are described in Lyon-Caen et al. (2006). Remeasurements were done in January 2006, (including 6 new sites first measured in 2003) using 9 Ashtech ZXTrem receivers with Geodetic IV antennas, and 3 Trimble 5700 receivers with Zephyr Geodetic antennas. All sites were occupied for at least two sessions of 12h to 24h, with two sites that were measured continuously during six and ten days (PIN and COB, respectively, figure 2), as in 1999 and 2003.

The three sites in El Salvador were measured in February 2003 during the campaign in Guatemala, with 48h of occupation at each site, using Ashtech Z12 receivers and Geodetic III and IIA antennas. They were remeasured in march 2006 using Z-Max Thales receivers and antennas, together with the ZAC guatemalan site (figure 2), during four consecutive, 10h-long daily sessions.

Measurements in Chiapas, conducted by UNAM (Universidad Nacional Autónoma de México), began in 2002 and were repeated

each year until 2005. Leica SR520 receivers were used with Leica A504 Dorne Margelin antennas. Each site was measured during two to five 24h sessions. Table A1 in Supporting Information summarizes the sites occupation.

2.2 Processing strategy

We use the GAMIT software (King and Bock, 2002) to process data from the campaign and permanent stations mentioned above. The GAMIT unconstrained solutions of daily station coordinates and their associated covariances are combined with selected SOPAC (Scripps Orbital and Permanent Array Center) solutions, using GLOBK (Herring, 2002), to obtain stations positions and velocities in the ITRF2000 reference frame. Velocity uncertainties are estimated using a Markovian error model during the GLOBK daily solution combination (Herring, 2002). We authorize for each station a random walk of $2 \text{ mm}/\sqrt{yr}$ around their position. Velocity vectors are determined without introducing a Markovian noise.

Several earthquakes occurred within our regional network between 1999 and 2006. We select all earthquakes with an hypocentral depth shallower than 30 km, and the $M_w \geq 6$ deeper earthquakes that are located within 500 km from the center of our study area (15.1°N , 269.7°E). We estimate their rupture parameters (slip and rupture size), based on the CMT catalog and scaling laws (Wells & Coppersmith, 1994). For the 2001, $M_w=7.7$ earthquake in El Salvador in particular, these parameters are given by Bommer et al. (2002) and Vallée et al. (2003). We use an elastic half-space model (Okada, 1985) to estimate the cumulative coseismic displacements associated with the selected earthquakes at each GPS site (Tables A2 and A3), and take them into account during the GLOBK combination process. This changes velocities by up to 1.8 mm/yr for site CON in eastern Guatemala (figure 2) but no more than 1mm/yr for the other sites.

Due to the short overlapping in time between measurements made within the Guatemala/El Salvador sub-network, and those made within the Chiapas sub-network (Table A1), we first compute two independent GLOBK velocity solutions for these two sub-networks, following the procedure described above. While both referenced to ITRF2000 with comparable residuals ($\sim 5 \text{ mm}$ on positions, 1.3 mm/yr on velocities for Guatemala/El Salvador, $\sim 4.5 \text{ mm}$ on positions, 2.5 mm/yr on velocities for Chiapas), the two resulting velocity fields are not fully consistent, with common sites such as TPCCH showing different velocity vectors (figure A1a). To make both velocity fields consistent, we use the more robust Guatemala/El Salvador solution as a reference, and we estimate the angular velocity that best adjusts the Chiapas velocity vectors with the Guatemala/El Salvador ones, at the common regional site TPCCH and at the IGS stations used by GLOBK for the stabilization in ITRF2000 (figure A1a). We use the same strategy to adjust the resulting Guatemala-El Salvador-Chiapas velocity field to that of DeMets et al. (2007) in ITRF2000 (figure A1b). Angular velocities used to obtain the ITRF2000 velocities (Table 1) are listed in Table A4.

This procedure allows us to use the CA/ITRF2000 and NA/ITRF2000 angular velocities estimated by DeMets et al. (2007) (Table A5) to reference our final regional velocity field in the CA and NA reference frames (figure 3). Note that we do not propagate the uncertainties of the angular velocities into the uncertainties of our sites velocities in these two frames. We estimate them to be on the order of 1 mm/yr at our regional stations, by comparison with velocity fields obtained using different values of the CA/ITRF2000

Table 1. GPS sites information. Lon, Lat, V_e , V_n , σ_e , σ_n , σ are longitude, latitude, east and north velocities referenced to ITRF2000, east and north standard errors and form factor, respectively. Sites in bold are permanent sites, * indicates velocities calculated by DeMets et al., 2007.

Lon ($^\circ\text{E}$)	Lat ($^\circ\text{N}$)	V_e	V_n	σ_e	σ_n	σ	Site
Chiapas							
266.063	16.225	-5.46	1.53	1.27	1.23	-0.027	AZTE
267.307	16.125	-2.61	5.67	1.30	1.23	-0.017	CONC
267.927	15.696	-1.25	6.86	1.28	1.23	-0.021	ESPI
266.396	15.935	-4.98	4.63	1.27	1.23	-0.024	ESPO
267.143	16.419	-4.84	1.71	1.56	1.50	0.002	GRUT
267.106	15.459	-2.00	4.33	1.27	1.23	-0.023	MAPA
267.611	15.281	-2.07	9.92	1.28	1.23	-0.041	SELE
267.481	16.675	-4.64	4.12	1.30	1.23	-0.014	SOLE
267.704	14.883	-0.96	6.72	1.53	1.49	-0.026	TPCH
Guatemala							
270.182	15.605	-3.25	0.44	1.29	1.16	0.028	CAH
270.941	15.394	-0.3	-0.66	1.38	1.21	0.075	CAM
270.348	14.779	9.25	4.71	1.25	1.14	0.053	CHI
269.618	14.075	5.45	4.79	1.36	1.18	0.026	CHL
269.196	14.638	2.33	0.87	1.25	1.14	0.035	CML
269.611	15.464	-2.53	0.24	1.20	1.10	0.087	COB
270.548	14.517	12.73	4.84	1.26	1.15	0.040	CON
270.760	14.854	5.09	3.22	1.87	1.23	0.052	CPJ
270.132	16.916	-6.78	-0.32	1.21	1.19	0.024	ELEN
269.478	14.590	3.20	2.80	1.71	2.40	-0.118	GUAT*
270.385	15.030	1.89	0.74	1.31	1.19	0.026	HON
268.531	15.282	-1.24	1.03	1.31	1.17	0.052	HUE
268.497	15.318	-2.65	3.76	1.22	1.20	0.063	HUEH
269.174	15.011	-3.22	0.36	1.27	1.21	0.003	JOY
268.450	14.537	2.55	3.16	1.66	1.47	-0.200	MAZ
270.329	15.084	1.42	1.41	1.26	1.15	0.039	MIN
270.766	15.930	-5.63	0.36	1.31	1.21	0.040	MOD
269.370	15.458	-2.42	4.7	1.23	1.20	0.043	PAM
269.620	14.551	7.62	2.39	1.20	1.10	0.098	PIN
268.486	14.871	0.53	-2.51	1.28	1.14	0.051	QUE
269.553	15.990	-5.52	0.73	1.26	1.15	0.046	RUB
269.719	15.075	0.09	1.38	1.29	1.16	0.038	SAL
269.751	14.816	6.02	1.41	1.26	1.15	0.054	SAN
268.506	15.571	-2.61	1.37	1.29	1.16	0.044	SOL
269.130	15.348	-5.08	-1.92	1.24	1.20	0.061	USP
270.499	14.981	5.45	4.92	1.47	1.30	0.012	ZAC
El Salvador							
270.680	13.495	-0.69	13.05	1.39	1.29	0.010	SIGN
270.883	13.697	4.48	8.60	1.40	1.00	0.500	SSIA
270.895	14.175	10.37	5.39	1.38	1.29	0.010	TEJU
270.500	14.116	12.67	5.17	1.38	1.29	0.010	TEXW
Honduras							
272.794	14.090	8.90	5.70	1.60	1.20	0.000	TEGU*

and NA/ITRF2000 angular velocity within their error bars. We neglect them in the following.

3 GPS VELOCITY FIELD AND ANALYSIS AT FAULT SCALE

Figure 3 illustrates the complexity of the velocity field in the CO/CA/NA triple junction area. We first describe its main features

Figure 3. GPS velocity field from table 1 in (a) North America and (b) Caribbean plates reference frames. Euler NA/ITRF2000 and CA/ITRF2000 angular velocities as well as velocity vectors of sites GUAT and TEGU (white arrows) are from DeMets et al. (2007). Dark gray bold lines outline active faults (names as in Figure 2). Light gray lines indicate location of profiles shown in Figure 4. Dotted line follows volcanic arc.

in the NA and CA reference frames before analyzing the slip partitioning among the different faults, the volcanic arc and the subduction zone.

3.1 Overall description

In the North America reference frame, the three sites ELEN, RUB and MOD, to the north, form a consistent group with small residual velocities (Figure 3a), comparable to those of sites CHET, VILL and CAMP on the Yucatan peninsula. On the first order, they can be considered as part of the stable North America plate, as the Yucatan sites (Marquez-Azua & DeMets, 2009).

In the Caribbean reference frame, the three sites CON, TEXW and TEJU show small residual velocities and can be considered at the first order as representing the stable Caribbean plate (Figure 3b). In the western, wedge-shaped part of the plate in between the Motagua fault and the volcanic arc, an east-west internal extension is observed across the grabens, confirming results from Lyon-Caen et al. (2006).

Figure 3 also shows the overall left-lateral motion between the NA and CA plates and the associated velocity gradient across the Polochic and Motagua faults. In the NA frame, all stations in Chiapas have a consistent motion towards north-east, roughly perpendicular to the trench, suggesting coupling at the CO/NA slab interface (Figure 3a). In contrast, in the CA frame, the velocities of the coastal sites south of the volcanic arc are mostly trench-parallel (Figure 3b). This could result from a low coupling at the CO/CA slab interface, as already proposed by Lyon-Caen et al. (2006). However, the velocities in El Salvador also indicate a right-lateral motion across the volcanic arc relatively to the stable CA plate (Figure 3b). The velocity field in southern Guatemala thus reflects the combined effects of coupling at the CO/CA interface and motion across the arc.

3.2 Strain partitioning across the major tectonic structures

Assuming first that the effect of the CO subduction on the velocity field is low in Guatemala and El Salvador (Lyon-Caen et al., 2006), we quantify the slip rates across the Polochic-Motagua faults (PMF), the grabens south of them and the volcanic arc, and

refine the previous analysis by Lyon-Caen et al. (2006), taking advantage of the network densification and remeasurement. We project the ITRF2000 velocities along 3 north-south trending profiles (East E, Central C, and West W) roughly perpendicular to the Polochic and Motagua faults (Figures 3b, 4a, 4d, 4f). We also project the horizontal CA-fixed velocities along a southern, east-west trending profile (South S) perpendicular to the grabens (Figure 3b and 5).

3.2.1 The Polochic-Motagua fault zone

We first use a one fault, half-space elastic model (e.g. Savage and Burford, 1973) as in Lyon-Caen et al. (2006). We invert for the interseismic velocity, the locking depth and the location of the fault trace along profiles E and C (Figures 4a to e). While strain accumulation is clearly concentrated on the northern trace of the Motagua fault on profile E, it seems offset by ~ 15 km north of it on profile C. Based on the $\chi^2=1$ contour, the far-field velocity and locking depth ranges are 18-22 mm/yr (best fit 20 mm/yr) and 14-28 km (best-fit 20 km) for profile E (best constrained model), and 14-26 mm/yr (best fit 20 mm/yr) and 12-66 km (best-fit 39 km) for profile C. The 20 km best-fit locking depth for profile E is consistent with the maximum depth of the seismogenic zone across the Polochic-Motagua fault system, derived from the present crustal seismicity distribution (Franco et al. 2009). We thus assume a constant 20 km locking depth along the entire fault system, and favor a model with a velocity of 20 mm/yr across profile E, decreasing to 16 mm/yr across profile C (figures 4a to 4e). At least 4 mm/yr seems to be accommodated by the PMF across profile W (velocity difference between SOL and QUE, figure 4f), although the limited length of the profile and its small number of sites do not allow any elastic modeling.

The new data set and analysis thus confirm the decrease of the far-field velocity across the PMF from eastern to western Guatemala, probably tending towards zero in the triple junction area. It also confirms the dominant role of the Motagua fault with respect to the Polochic fault in the accommodation of the deformation associated with the NA and CA relative motion (Lyon-Caen et al., 2006). An homogeneous half-space elastic model including the two faults (with a fixed location) shows that at least 88% of the total strain is accommodated by the Motagua fault in the eastern part of Guatemala (Figure 4c). This fault is generally considered as the geological boundary between the NA and the CA plates (e.g. Carfanten, 1986; Donnelly et al., 1990; Martens et al., 2007). However the area in between the Polochic and Motagua faults is a wide complex metamorphic zone. Furthermore there is no doubt on the Holocene activity of the Polochic fault as attested by the similarities of its morphology, Holocene slip rate, historical and present-day seismicity with that of the Motagua fault (Carr, 1976, Burkart, 1978, Schwartz et al., 1979, Burkart 1983, White, 1985, White and Harlow, 1993, Ambraseys and Adams, 2001, Kovach 2004, Franco et al. 2009, Suski et al. 2009). The lack of strain accumulation across the Polochic fault remains a puzzling result. We investigate below the possible influence of rigidity contrasts across the Polochic-Motagua fault zone and of post-seismic effects following the 1976 earthquake on the present-day velocity field.

A recent Receiver Function study suggests variations of the Moho depth (resp. Vp/Vs ratio) across the Polochic and Motagua faults (Franco et al. 2009), with a Moho depth thinner by 4-6 km (resp. a Vp/Vs decreased by 6-7%) in between the two faults. Such variations, that are likely related to the geological history of this region, could result in asymmetric velocity profiles across faults, as-

Figure 4. (a) Topography (top) and ITRF2000 GPS velocities projected onto fault-parallel components along eastern profile, E (bottom), with fit model for a locking depth of 20 km. Main active fault traces are indicated by dotted lines. Volcanic arc area is shaded. (b) $\chi^2 = 1$ contour line for locking depth and rate estimated using half-space elastic modeling (see section 3 in text). Cross shows model for a 20 km locking depth (best-fit). (c) $\chi^2 = 1$ contour line for a two fault model, showing the relative contribution of the Polochic fault to the NA/CA motion, as a function of the asymmetry coefficient K across fault (Le Pichon et al., 2005). Case K=0 corresponds to an homogeneous half-space model. (d) and (e): same as (a) and (b), respectively, for central profile, C. Shaded area on (e) is that consistent with the locking depth range estimated from eastern profile in (b). (f): same as (a) and (d) for western profile, W. See Figure 3 for the location of profiles.

Figure 5. Topography and GPS vectors in CA plate reference frame projected perpendicularly to the mean grabens orientation along southern profile, S. Sites names are indicated at bottom. See Figure 3 for the location of profiles.

sociated with contrasts in elastic parameters or elastic thicknesses on both sides of the faults (Le Pichon et al., 2005; Schmalzle et al., 2006; Chéry, 2007; Jolivet et al., 2008). Our tests on velocities of profile E, using a modified half-space elastic model taking into account asymmetry (formulation of Le Pichon et al., 2005), still show that the Polochic fault does not accommodate more than $\sim 15\%$ of the total deformation (figure 4c).

To estimate the contribution to the present-day velocity field of postseismic relaxation related to the 1976 earthquake, we use a 3D-viscoelastic model developed by Yu et al. (1996). We consider an elastic layer, with a thickness $H=30$ km and a shear modulus $\mu = 3.10^{10}$ N.m, above an homogeneous viscous half-space, characterized by a viscosity η ranging from 10^{18} to 10^{21} Pa.s. The 1976 rupture on the Motagua fault is modeled using an infinitely-long vertical fault extending from the surface to a depth of 15 km, with an homogeneous coseismic slip of 1.5 m consistent with field observations by Plafker et al. (1976). Figure A2 shows the modeled post-seismic displacements as a function of time normalized by the relaxation time ($\frac{t}{\tau}$, with $\tau = 2\frac{\eta}{\mu}$), for various distances y from the fault. Maximum velocities related to postseismic relaxation are on the order of 0.6 mm/yr: 0.4 cm between the 1999 and 2006 GPS campaigns, at a distance of 40 km from the Motagua fault trace and for a viscosity of 10^{19} Pa.s. In any case, we conclude that postseismic effects can not explain the apparent lack of strain accumulation across the Polochic fault.

3.2.2 East-West Extension

The southern profile S shows an extension rate of ~ 9 mm/yr across the Caribbean graben series north of the volcanic arc, between sites TEJU to the east and TPCH in south-western Chiapas (figure 5). This gives only a first order estimate as we do not take into account the rotation of microblocks separating the active grabens. Most of the extension is concentrated across the Guatemala city grabens (rate of 5 ± 2 mm/yr), which confirms previous estimation by Lyon-Caen et al. (2006). The remaining extension, given our GPS network geometry and error bars, is not clearly localized on specific structures. Seismicity and fault plane solutions (Guzman-Speziale, 2001; Caceres et al., 2005; Franco et al., 2009), as well as complementary GPS observations (Rodriguez et al., 2009; note that data are referenced to ITRF2005 instead of ITRF2000 in this study) and finite element modeling (Alvarez-Gomez et al., 2008) in northern central America indicate that some extension is accommodated eastward from Guatemala city, up to north-eastern Honduras, across the Ipala graben and the depression of Honduras in particular.

3.2.3 Volcanic arc

In the Caribbean plate reference (figure 3b), GPS sites along the coast in Guatemala and El Salvador (TPCH, MAZ, CHL, SIGN, SSIA) show velocity vectors parallel to the Mid-America Trench (MAT), consistent with dextral motion across the volcanic arc at a rate of up to 14mm/yr in El Salvador (see TEJU-SSIA-SIGN velocity gradient in figure 4a). Such dextral shear is in agreement with previous GPS measurements in Guatemala by Lyon-Caen et al. (2006). Similar rates are also observed by GPS in El Salvador and Nicaragua ($\simeq 15$ mm/yr; Turner et al., 2007; Correa-Mora et al., 2009; Alvarado et al., 2011) and Costa-Rica (Norabuena et al., 2004) or attested by dextral mechanisms of recent crustal earthquakes (M6.6, 02/13/2001 earthquake in El Salvador

in particular, Canora et al., 2010). It can be interpreted as dextral slip on a northwest-striking, intra-arc, sub-vertical fault, bounding to the north an independent forearc sliver. Such dextral fault system within the volcanic arc has been evidenced in the field in El Salvador (Martinez-Diaz et al., 2004; Corti et al., 2005). Satellite images and topography analysis suggest that it may continue westwards under the volcanic deposits in Guatemala (Carr, 1976). In Nicaragua, Lafemina et al. (2002) suggest that the dextral shear is rather accommodated by book-shelf faulting involving northeast-striking left-lateral faults perpendicular to the trench. Slip partitioning related to the obliquity of the convergence of the Cocos plate has been proposed to explain the observed dextral shear across the arc (DeMets, 2001). However, it would require strong coupling along the subduction interface, in contradiction with the most recent studies (Lyon-Caen et al., 2006; Turner et al., 2007; Correa-Mora et al., 2009, this paper). Instead, the trench-parallel, north-westwards, forearc motion may be related to the indentation of the Cocos ridge on the Caribbean plate, offshore Costa Rica (LaFemina et al., 2009; Alvarado et al., 2011).

4 REGIONAL MODELING OF THE VELOCITY FIELD

To refine the proposed first-order interpretation of the crustal deformation, we model the GPS velocity field using the 3D-inversion method DEFNODE developed by McCaffrey (2002). GPS velocities are considered as resulting from the combination of relative block rotations and elastic deformation due to coupling at the block boundaries. The relative block motions are defined by spherical Earth angular velocity vectors (Euler rotation poles and rates) while the interseismic deformation is modeled as backslip on the faults that separate blocks (Okada, 1985; Savage, 1983). The faults at the boundary of the finite blocks are defined in 3D, by a series of nodes along the fault planes (forming an irregular grid of points along strike and down dip). Fault locking is parameterized at each node by a coupling factor ϕ , which represents the fractional part of the relative block motion that is not accommodated by steady, aseismic slip. ϕ ranges between 0 (no coupling) and 1 (full coupling). Block angular velocities and coupling factors ϕ can be inverted by minimizing the misfit between observations (e.g. GPS velocities and slip vectors) and predicted data, using a simulated annealing method.

4.1 Input data, model geometry

We constrain our models using the horizontal GPS velocities and their associated uncertainties listed in Table 1. However, given the poor density of points that defines the east-west extension in the westernmost part of the Caribbean plate, we can not model this extension and do not take into account velocities at sites QUE, CML, GUAT, PIN (Figure 3). We also use slip vectors of subduction earthquakes of $M_w \geq 5.9$ (Table 2) from the complete CMT catalog, to provide constraints on the slip direction along the subduction plane.

We define two sets of model geometries : (1) a 3 blocks (North America, NA, Caribbean, CA, and Cocos, CO) and 2 faults (Motagua fault, MF, and Middle-America Trench, MAT) model, called 3B model hereafter, and (2) a 4 blocks (NA, CA, CO, and the forearc microplate, AR) and 3 faults model (MF, MAT, and the Volcanic Arc Fault, VAF), called the 4B model (figure 6). The MF that marks the NA/CA boundary follows the Motagua fault surface

Table 2. Selected earthquakes from CMT-Harvard catalog with slip vector azimuths to constrain slip direction along the subduction (see section 4 in text).

Long. (°E)	Lat. (°N)	Azimuth (°)	Depth (km)	Magnitude CMT Mw	Reference CMT
272.84	12.7700	38	40.3	6.5	053178A
268.95	13.8800	33	25.0	6.3	103078A
270.36	13.1500	31	29.4	6.1	120678B
269.12	13.8300	27	29.8	6.8	102779A
269.27	13.7800	26	27.6	6.8	102779B
267.89	14.2700	36	42.6	5.9	040682A
268.06	14.0500	27	31.0	7.0	120283A
273.44	11.5900	34	54.6	6.1	082384A
273.44	11.9300	40	50.0	6.1	041985A

trace to the east. To the west, we extrapolate this fault trace under the volcanic deposits, and connect it to the Polochic fault near the Mexican border, then to the MAT (Figures 2 and 6). The MF is considered as a vertical fault. The VAF, defined as a vertical fault as well, is the continuation to the west, below the volcanic arc, of the well known trace of the dextral fault that runs from Costa-Rica to northern Salvador (e.g. Corti et al., 2005). We use the bathymetry and the microseismicity distribution relocated by Engdhal & Villaseñor (2002) to delineate the depth contours of the Cocos plate slab (Figure 6).

4.2 Model parameters

For both the 3B and 4B models, the CO and NA angular velocity vectors relative to the CA block are from DeMets et al. (2007) and DeMets et al. (1990) (Nuvel1-A), respectively. There is no clear evidence neither onland, nor offshore, nor in the seismic activity, that the western continuation of the MF west of its junction with the volcanic arc (named MF_w hereafter, Figure 6), exists and is active. As we need to materialize all block limits between the CO/NA/CA plates in the DEFNODE model, we assign to MF_w a uniform full coupling, from the surface down to 250 km. This is equivalent in the model to considering that the AR block is pinned to the NA block (Alvarez-Gomez et al., 2008; Rodriguez et al., 2009). In any case,

Figure 6. 4 blocks (4B) model geometry. The NA, CA, CO and AR blocks are delimited by 3 faults: the Mid-America Trench (MAT), the Volcanic Arc Fault (VAF) and the Motagua Fault (MF, noted MF_w west of its junction with VAF). The 3 blocks (3B) model follows the same geometry, with AR and CA blocks combined into a single CA block.

Figure 7. Inverted coupling coefficients along the MF_e , MF_c , MAT_{ch} and MAT_{gs} , and residual velocities for best-fit 3B model.

the geodetic data onland would not allow to test other hypothesis. We have tested that our main conclusions are not sensitive to this modeling choice.

In the 3B model, we invert for the coupling along the MF (east of MF_w , Figure 6) and the MAT. In the 4B model, we fix the coupling along the MF according to the results from the 3B model and invert for the coupling along the VAF, MAT and for the AR/CA angular velocity (Figure 6). We discuss the trade-off between the inverted parameters.

Along the MAT subduction interface, we assume that coupling can occur down to 25 km depth (Marquez-Azua & DeMets, 2003; Lyon-Caen et al., 2006). The locking depth along the MF is initially fixed to 20 km, as deduced from the analysis in section 3.2.1, and to 15 km along the VAF (same order of magnitude as found eastward in El Salvador, Correa-Mora et al., 2009).

A series of resolution tests (Figure A3) indicate that our data distribution allows to constrain along-strike variations of coupling on the subduction interface while along-dip variations can not be resolved.

4.3 Results

4.3.1 3B models

Given the complex internal deformation (extension in the western part, dextral slip across the volcanic arc) within the CA block as defined in the 3B model, this model obviously can not account for the observed GPS velocities on the CA block. We thus only consider the GPS vectors on the NA block for this first set of models.

We start from a simple parametrization of the MF and MAT (same coupling factor at all nodes for each fault) and progressively allow for potential along-strike variations in the coupling. The analysis of the residual velocities of this series of test models shows that, given our data distribution, a model with two sections along the MF (MF_e , MF_c for the east and central sections, respectively) as well as along MAT (MAT_{ch} and MAT_{gs} under Chiapas and Guatemala/El Salvador respectively), is a good compromise to account for the observed GPS velocities (Figure 7). Assuming a constant locking depth of 20 km all along the MF (see discussion in section 3.2.1), the resulting 3B model shows a decreasing coupling on the fault from eastern ($\phi=0.9$ along MF_e) to central ($\phi=0.38$ along MF_c) Guatemala (Figure 7). We interpret these coupling lateral variations as resulting from the westwards velocity decrease on the MF. The coupling values correspond to average velocities of 18

Figure 8. Same as Figure 7 for best-fit 4B model, with coupling along VAF fixed to 1.

mm/yr and 8.5 mm/yr along the MF_e and MF_c respectively. These velocities that represent average values on fault section are consistent with that deduced from the elastic half-space modeling on local profiles in section 3.2.1. Figure 7 also shows the resulting coupling along the subduction zone below Chiapas that is fairly high ($\phi=0.79$ along MAT_{ch}) compared to the coupling below Guatemala and El Salvador ($\phi=0.34$ along MAT_{gs}). This apparent contrast of coupling is better constrained and discussed from the 4B models below.

4.3.2 4B models

All GPS vectors are now inverted after fixing the coupling along the MF_e and MF_c to the values estimated in the previous section. Coupling along the VAF is considered uniform given our data distribution, although we would expect it to decrease westwards, as along the MF, due to the CA plate internal extension.

Assuming first that the VAF is fully locked on the upper 15 km ($\phi_{VAF}=1$, corresponding to a velocity of 15 mm/yr), the best fit model (Figure 8) also shows lateral variations of coupling along the subduction zone as in model 3B, with a CO/NA high coupling offshore Chiapas ($\phi=0.61$ along MAT_{ch}), and a CO/AR low coupling south of the volcanic arc offshore Guatemala and El Salvador ($\phi=0.25$ along MAT_{gs}). However there is a trade-off in the inversion of the forearc velocity field between the contributions of the AR/CA rotation and the coupling along the VAF and MAT in Guatemala and El Salvador. In order to evaluate these relative contributions, we fix the CO/NA coupling ($\phi=0.61$ along MAT_{ch} , figure 9) and run a series of inversion of the AR/CA angular velocity for different sets of coupling along the VAF and the MAT_{gs} . Note that in El Salvador, Correa-Mora et al. (2009) suggest that ϕ_{VAF} is larger than 0.85.

All best fit models indicate a CO/AR coupling ($\phi_{MAT_{gs}}$) around 0.25 ± 0.1 , independently of the ϕ_{VAF} value (Figure 9), confirming the contrast with the CO/NA coupling ($\phi_{MAT_{ch}}$). Pacheco et al., 1993 estimated a low coupling value along the CO subduction interface (0.2), from the analysis of the cumulative seismic moment during the XXth century. However, this was an "averaged" value from Chiapas to Costa Rica. A GPS-derived, low coupling value offshore El Salvador was obtained more recently by Correa-Mora et al. (2009), consistent with our results.

Figure 9. Reduced χ^2 as a function of $\phi_{MAT_{gs}}$, for ϕ_{VAF} fixed to 0, 0.5 and 1. $\phi_{MAT_{ch}}$ is fixed to 0.61. Only the Euler AR/CA rotation parameters are inverted.

5 SUMMARY AND DISCUSSION

The new GPS measurements presented herein represent the first from the Chiapas region of Mexico, complement previous work from Guatemala and El Salvador, and enable the refinement of regional kinematic models previously proposed for the Cocos-North America-Caribbean plate triple junction (Lyon-Caen et al., 2006; Plafker, 1976). The joint analysis of our results from the elastic half space modeling (section 3) and the DEFNODE block modeling (section 4) of the GPS velocity field brings new constraints on the kinematics of the active structures as well as on the coupling along the subduction zone, as summarized in figure 10. Our results are in overall agreement with recent models based on GPS data in El Salvador, Honduras and Nicaragua and on geological and strain rate data (Alvarez-Gomez et al., 2008, Correa-Mora et al., 2009; Rodriguez et al., 2009).

5.1 Regional fault kinematics

The Motagua fault concentrates the present day strain accumulation due to the NA/CA relative motion. The absence of resolvable strain accumulation across the active Polochic fault cannot be explained in the modeling by postseismic relaxation or rheological lateral variations. This suggests that slip on the Polochic and Motagua faults may vary with time as a result of mechanical interactions within this strike slip fault system. Transient slip rate and activity switch between faults have already been observed from geodesy (east California shear zone, Peltzer et al., 2001), or from historical seismicity analysis and modeling (north and east Anatolian fault, Hubert-Ferrari et al., 2003).

The NA/CA motion decreases from 18-22 mm/yr in eastern Guatemala to 14-20 mm/yr in Central Guatemala assuming a uniform locking depth of 14-28 km (best constrained by profile E, Figure 4) and to ~ 4 mm/yr in western Guatemala. West of the Mexican border, the Motagua fault likely connects with the Polochic fault but does not accommodate any significant deformation. The east-west extension across the grabens in Guatemala at a rate of ~ 9 mm/yr is mostly localized on the Guatemala city graben (~ 5 mm/yr), while the remaining part is not clearly localized on specific grabens. A more complete discussion of the extension accommodation from western Guatemala to Honduras would require a joint analysis of all regional GPS data in a common reference frame. Up to 15 mm/yr of dextral motion could be accommodated across the

Figure 10. Proposed model of faults kinematics and coupling along the Cocos slab interface, revised from Lyon-Caen et al. (2006). Numbers are velocities relative to CA plate in mm/yr. Focal mechanisms are for crustal earthquakes (depth ≤ 30 km) since 1976, from CMT Harvard catalog.

volcanic arc in El Salvador and southeastern Guatemala, consistent with estimations by Alvarado et al. (2011) in El Salvador and Nicaragua.

Kinematically, the extension in the western wedge of the Caribbean plate requires a westward decrease of both the Polochic-Motagua fault slip-rate and the volcanic arc fault slip-rate (figure 10). This decrease can only be partly modeled herein given the limited spatial sampling of our velocity field.

5.2 Lateral coupling variation along the Mid-America Trench

The coupling along the Cocos subduction zone varies along the Mid-America Trench with a fairly high coupling (~ 0.6) offshore Chiapas and a low coupling offshore Guatemala (~ 0.25).

Lateral variations of coupling along subduction zones have been evidenced by cumulative seismic moment and geodetic studies in many areas (e.g. Pacheco et al., 1993). In recent years, the increasing space and time density of GPS data, in particular, have allowed to obtain maps of interseismic coupling along subduction interfaces, that are generally interpreted in terms of seismic hazard assessment, as in Sumatra (Prawirodirdjo et al., 1997, Chlieh et al., 2008), Kamchatka (Bürgmann et al., 2005), the Aleutian Islands (Cross & Freymueller, 2007) or South America (e.g. Pritchard & Simons, 2006, Ruegg et al. 2009, Perfettini et al. 2010). Segments with high coupling in the seismogenic zone are considered as the loci of large ($M > 8$) mega-thrust earthquakes, while segments with low coupling are associated with aseismic slip and moderate seismicity. Such along-strike variations of coupling are likely representative of heterogeneities in the mechanical properties at the interface. They are assumed to be rather stable in space and time through successive seismic cycles, although it may depend on their origin. A correlation between the degree of coupling and the age of the subducting lithosphere or the convergence rate has been suggested by Ruff & Kanamori (1983), in contradiction with more recent studies (Heuret & Lallemand, 2005) and the occurrence of mega-thrust earthquakes in Sumatra (2004 Sumatra-Andaman) and Japan (2011 Tohoku-oki). High coupling areas along subduction zones may be spatially correlated with forearc basins or thick sediments in the trench, and associated with negative free air gravity anomalies (e.g Ruff, 1989, Wells et al., 2003, Song & Simons, 2003, Bürgmann et al., 2005, Loveless et al., 2010). Low coupling areas

have also been correlated with the location of subducting ridges or seamounts (e.g. Cloos et al., 1992).

The analysis of free air gravity anomalies and marine seismic profiles offshore Mexico and Central America allows to derive a map of sediment thickness in this region (Divins et al., 2003). Lateral variations of both Bouguer gravity anomalies and sediment thickness are observed offshore Chiapas and Guatemala (Figure 11). The observed gradients, although rather low, would be consistent with, and may explain the coupling decrease at the subduction interface that we model (figure 8) from Chiapas to Guatemala and El Salvador (Song & Simons, 2003). However, the historical seismicity, although poorly documented (White et al., 2004), does not reveal any clear lateral variations of the seismic behavior along the subduction zone. Several $M7.5 - 8.1$ subduction earthquakes are reported, that seem to release less than 50% of the accumulated slip (White et al., 2004). This would be consistent with the overall low coupling values (0.25-0.6) that we model. The significance of such low values and of their lateral variations, in terms of seismic hazard for the study area, as well as their permanent or transient feature, thus remain open questions.

ACKNOWLEDGMENTS

This work was partly funded by INSU-CNRS DyETI program. We thank the guatemalan institutions INSIVUMEH, CONRED, IGN, CUNOR and CESEM from USAC, as well as the IGN in El Salvador, for their unvaluable logistic support. The french embassy in Guatemala provided help during field surveys. We thank Christophe Vigny for his help with GAMIT/GLOBK software and discussions concerning reference frames. We thank Christel Tiberi for help with the gravity data and Eric Calais for discussions concerning coupling on slab interface. We thank Charles DeMets and an anonymous reviewer for their constructive comments.

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Figure 11. Maps of (a) bathymetry, (b) marine sediment thickness (Divins et al., 2003; <http://www.ngdc.noaa.gov/ngg/sedthick/sedthick.html>) and (c) Bouguer gravity anomalies (calculated from raw data given by the Bureau Gravimétrique International (BGI)). GB in (a) is for Guatemala Basin. See discussion in text.

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Table A1. Occupation history of campaign GPS sites

Site	Measurement duration (days)					2006
	1999	2002	2003	2004	2005	
Chiapas						
AZTE		3.2	3	2.5	2.6	
CONC		3	2.7	2.5	3	
ESPI		4	2.3			
ESPO		3.2	2	2.5	2.6	
GRUT				2	2	
MAPA			2	2.6	3	
SELE		3.6	2.5	3	2.8	
SOLE		3	3.3	3.2	3	
Guatemala						
CAH	2		2			2
CAM			1.4			2
CHI	2		4			4
CHL	2		2			4
CML	2		1.8			4
COB	8		7.3			8
CON	2		2.5			2+2
CPJ			1.8			2
HON	2		2.7+0.5			2
HUE	2		2			2
JOY			0.6			2
MAZ	2		2			2
MIN	2		4			3
MOD			1.3			2
PAM			2			2
PIN	8		9			5
QUE	2		3			2
RUB	3		3			4
SAL	2		2			2
SAN	2		1			2
SOL	2		2			2
USP			2			2
ZAC			2			4
El Salvador						
SIGN			2			4*0.5
TEJU			2			4*0.5
TEXW			2			4*0.5

Figure A1. (a) ITRF2000 velocity field for the Guatemala/El Salvador GPS sub-network (black arrows), Chiapas sub-network (gray arrows) and DeMets et al. (2007) solution (white arrows), before adjustment to a common reference frame (see processing strategy in text and Table A5). Inset shows common IGS permanent sites used in GLOBK (squares) and for reference frame adjustment (circles) for both Guatemala/El Salvador and Chiapas solutions. (b) ITRF2000 velocity field after adjustment (see Table 1).

Table A2. Cumulative coseismic displacement modeled at each station, for all events that occurred between 1999-2006 or 2003-2006. No estimate was done for sites ELEN, GUAT and SSIA (we use velocities computed by DeMets et al. (2007)).

Site	Cumulated displacement (mm)					
	1999-2003		2003-2006		1999-2006	
	East	North	East	North	East	North
CAH	2.06	4.51	0.01	-0.28	2.07	4.23
CAM	-	-	-0.14	-0.36	-0.14	-0.36
CHI	7.95	0.37	0.46	-1.25	8.41	-1.62
CHL	3.78	-7.07	0.14	-0.75	3.92	-7.82
CML	3.43	-3.62	0.05	-0.31	3.48	-3.93
COB	2.07	0.47	0.08	-0.2	2.15	0.67
CON	12.65	-3.45	-0.31	-1.62	12.34	5.07
CPJ	-	-	-0.33	-0.66	-0.33	-0.66
HUE	1.49	-1.02	0.04	-0.05	1.53	-1.07
HUEH	-	-	0.04	-0.05	0.04	-0.05
HON	5.99	3.99	-0.07	-0.63	5.92	3.36
JOY	-	-	0.1	-0.14	0.1	-0.14
MAZ	0.42	-2.10	0.22	-0.23	0.64	-2.33
MIN	5.52	3.77	-0.03	-0.61	5.49	3.16
MOD	-	-	-0.04	-0.21	-0.04	-0.21
PAM	-	-	0.08	-0.13	0.08	-0.13
PIN	5.37	-4.65	0.14	-0.61	5.51	-5.26
QUE	1.35	-1.78	0.09	-0.13	1.44	-1.91
RUB	0.43	1.82	0.04	-0.11	2.25	-0.07
SAL	4.09	-0.87	0.15	-0.37	4.24	1.24
SAN	5.28	-2.50	0.20	-0.54	4.74	-2.30
SOL	1.20	-0.52	0.02	-0.03	1.22	-0.55
USP	-	-	0.08	-0.09	0.08	-0.09
ZAC	-	-	-0.14	-0.52	-0.14	-0.52
SIGN	-	-	-0.68	-0.26	-0.68	-0.26
TEJU	-	-	-1.04	-1.27	-1.04	-1.27
TEXW	-	-	-1.27	-2.17	-1.27	-2.17
TPCH	-	-	0.04	-0.03	0.04	-0.03

Figure A2. Cumulative post-seismic displacements, estimated along a profile perpendicular to the Motagua fault, for each GPS campaign in 1999, 2003, 2006, corresponding to 23, 27 and 30 years after the 1976 Guatemala earthquake, respectively, and for viscosity of 10^{18} , 10^{19} , 10^{20} and 10^{21} Pa.s.

Table A3. Coseismic displacement (mm) modeled at each station, for each event that occurred between 1999-2006 or 2003-2006.

Date (YYMMDD), Mw	990508, 6.0		990711, 6.7		010113, 7.7	
Site	East	North	East	North	East	North
CAH	-0.04	-0.04	0.05	1.46	1.89	4.27
CHI	-0.05	-0.04	1.25	1.99	5.86	1.12
CHL	0.00	-0.01	0.48	0.55	5.12	-3.22
CML	-0.12	-0.09	0.32	0.45	2.75	-1.25
COB	-0.07	-0.08	-0.05	0.75	2.03	1.51
CON	-0.01	-0.01	1.12	1.94	9.37	-1.66
HON	-0.03	-0.02	1.59	2.40	3.79	3.50
HUE	-0.20	-0.31	0.05	0.28	0.94	-0.21
MAZ	-0.75	-0.56	0.13	0.41	0.51	-0.81
MIN	-0.03	-0.03	1.49	2.25	3.53	3.44
PIN	-0.05	-0.04	0.55	0.85	4.87	-1.75
QUE	-0.36	-0.55	0.06	0.44	1.22	-0.49
RUB	-0.05	-0.08	-0.96	0.68	1.22	2.26
SAL	-0.06	-0.06	0.46	0.94	3.26	0.54
SAN	-0.05	-0.04	0.53	1.00	4.46	-0.57
SOL	-0.08	-0.22	-0.23	0.31	1.16	0.27

Date (YYMMDD), Mw	010213, 6.5		010625, 5.2		021109, 6.0	
Site	East	North	East	North	East	North
CAH	-0.03	-0.02	0.52	-0.48	-0.09	-0.13
CHI	-0.01	-0.04	1.57	-1.81	-0.10	-0.11
CHL	0.01	-0.01	0.59	-1.10	-0.24	-0.30
CML	0.03	0.01	0.67	-0.66	-0.22	-0.62
COB	-0.18	-0.16	0.58	-0.61	-0.06	-0.12
CON	0.01	0.01	2.70	-3.19	-0.05	-0.05
HON	0.01	0.01	1.41	-1.21	-0.16	-0.08
HUE	0.01	0.03	0.45	-0.22	0.01	-0.10
MAZ	0.02	0.02	0.19	-0.39	0.06	-0.38
MIN	0.01	-0.02	0.99	-1.12	-0.06	-0.08
PIN	0.03	-0.04	1.11	-1.01	-0.21	-0.28
QUE	0.04	0.03	0.24	-0.31	0.04	-0.22
RUB	-0.04	-0.04	0.37	-0.40	-0.03	-0.10
SAL	0.10	-0.09	0.81	-0.83	-0.10	-0.18
SAN	0.06	-0.06	1.02	-1.09	-0.13	-0.20
SOL	-0.03	0.03	0.32	-0.30	-0.03	-0.14

Date (YYMMDD), Mw	030121, 6.4		030825, 5.9		041120, 6.3	
Site	East	North	East	North	East	North
CAH	-0.24	-0.55	0.08	0.07	-0.06	-0.32
CAM	-	-	0.04	0.04	-0.18	-0.42
CHI	-0.57	-0.74	0.07	0.08	-0.36	-0.65
CHL	-2.18	-2.98	-0.19	0.01	0.19	-0.70
CML	0.0	-1.46	0.05	0.04	0.05	-0.36
COB	-0.18	-0.82	0.10	0.11	-0.01	-0.31
CON	-0.49	-0.49	0.07	0.02	-0.50	-1.66
CPJ	-	-	0.07	0.06	-0.54	-1.01
HUE	0.23	-0.49	0.02	0.03	0.02	-0.09
HUEH	-	-	0.02	0.03	0.02	-0.09
HON	-0.62	-0.61	0.11	0.07	-0.18	-0.69
JOY	-	-	0.07	0.20	0.04	-0.31
MAZ	0.26	-0.39	0.21	-0.23	0.02	0.00
MIN	-0.41	-0.67	0.10	0.05	-0.11	-0.68
MOD	-	-	0.04	0.05	-0.09	-0.29
PAM	-	-	0.10	0.18	0.01	-0.32
PIN	-0.93	-2.38	0.11	0.12	0.13	-0.76
QUE	0.11	-0.68	0.11	-0.10	-0.01	-0.03
RUB	-0.08	-0.50	0.06	0.08	-0.01	-0.20
SAL	-0.38	-1.19	0.14	0.10	-0.01	-0.51
SAN	-0.61	-1.54	0.25	0.10	0.07	-0.68
SOL	0.09	-0.47	0.03	0.07	0.00	-0.10
USP	-	-	0.08	0.04	0.03	-0.14
ZAC	-	-	0.08	0.08	-0.30	-0.78
SIGN	-	-	-0.02	0.01	-0.72	-0.29
TEJU	-	-	0.02	0.02	-0.90	-1.68
TEXW	-	-	0.01	0.02	-1.21	-2.59
AZTE	-	-	0.00	0.00	0.00	0.00
ESPO	-	-	0.00	0.00	0.00	0.00
MAPA	-	-	0.00	0.00	0.00	0.00
SELE	-	-	-0.01	-0.01	-0.01	-0.01
ESPI	-	-	0.00	-0.02	0.00	-0.02
SOLE	-	-	0.00	-0.02	0.00	-0.02
GRUT	-	-	0.00	-0.02	0.00	-0.02
CONC	-	-	0.00	-0.01	0.00	-0.01
TPCH	-	-	0.05	-0.03	0.00	0.00

Date (YYMMDD), Mw	041213, 5.9		050518, 5.3	
Site	East	North	East	North
CAH	-0.01	0.01	0.00	-0.03
CAM	-0.02	0.01	0.02	0.01
CHI	-0.03	0.11	0.78	-0.79
CHL	0.07	-0.01	0.07	-0.05
CML	-0.01	0.01	-0.04	0.00
COB	-0.01	0.01	0.00	-0.01
CON	-0.01	0.31	0.13	-0.29
CPJ	0.01	0.12	0.13	0.17
HUE	0.01	0.01	-0.01	0.00
HUEH	0.01	0.01	-0.01	0.00
HON	-0.02	0.09	0.02	-0.10
JOY	0.01	-0.02	-0.02	-0.01
MAZ	0.01	0.00	-0.01	0.00
MIN	-0.02	0.07	0.00	-0.05
MOD	0.00	0.02	0.01	0.01
PAM	-0.01	0.01	-0.02	0.00
PIN	-0.03	0.04	-0.07	-0.01
QUE	0.00	0.00	-0.01	0.00
RUB	-0.01	0.01	0.00	0.00
SAL	-0.02	0.03	0.04	0.01
SAN	-0.03	0.04	-0.09	0.00
SOL	0.00	0.00	-0.01	0.00
USP	-0.01	0.01	-0.02	0.00
ZAC	-0.01	0.09	0.09	0.09
SIGN	0.06	0.02	0.00	0.00
TEJU	-0.18	0.40	0.02	-0.01
TEXW	-0.07	0.39	0.00	0.01
AZTE	0.00	0.00	0.00	0.00
ESPO	0.00	0.00	0.00	0.00
MAPA	0.00	0.00	0.00	0.00
SELE	0.00	0.00	-0.01	0.00
ESPI	0.00	0.00	-0.01	0.00
SOLE	0.00	0.00	0.00	0.00
GRUT	0.00	0.00	0.00	0.00
CONC	0.00	0.00	0.00	0.00
TPCH	0.00	0.00	-0.01	0.00

Table A4. Angular velocities used in this study. Ref 1: DeMets et al. (2007), Ref 2: DeMets et al. (1990) and DeMets et al. (1994).

Blocks	Reference	Eulerian poles			Errors					
		Latitude °N	Longitude °E	Rotation rate °.Myr ⁻¹	σ_{xx}	σ_{yy}	σ_{zz}	σ_{xy}	σ_{xz}	σ_{yz}
CA-ITRF2000	Ref 1	36.3	-98.5	0.255	0.	0.831	0.175	-0.262	0.000	-0.184
NA-ITRF2000	Ref 1	-7.64	-86.21	0.196	0.011	0.182	0.107	0.015	-0.011	-0.125
NA/CA	Ref 1	75.9	191.5	-0.182	0.143	1.013	0.282	-0.247	-0.011	-0.309
blocks	Reference	Latitude °N	Longitude °E	rotation rate(w) °.Myr ⁻¹	σ_{max} °N	σ_{min} °E	σ_w °.Myr ⁻¹			
CO/CA	Ref 2	24.1	-119.4	1.31	2.5	1.2	0.05	-	-	-

Table A5. Rotation parameters used to adjust the Guatemala/El Salvador, Chiapas, and DeMets et al. (2007) solutions in the same reference frame.

Solutions	Eulerian poles		
	Latitude ° N	Longitude ° E	Rotation rate °.Myr ⁻¹
Chiapas and Guatemala/El Salvador	-44.261	88.285	0.0085
Guatemala/El Salvador and DeMets et al. (2007)	-7.706	29.69	0.0058

Figure A3. Resolution tests for 3B models. (a): Forward model imposing along-strike and along-dip coupling variations along the subduction zone. (b): Coupling inverted from (a) and residual velocities. The synthetic GPS vectors obtained in (a) are associated with uncertainties from Table 1, and inverted for coupling along the MAT (all other parameters are fixed). Along-dip variations cannot be retrieved. (c): Same as (a) with along-strike variations of coupling only. (d): Same as (b). Lateral variations are well retrieved by inversion.